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(54) SEISMIC CABLE

(71) We, TEXAS INSTRUMENTS INCORPORATED, a Corporation organized according to the laws of the State of Delaware, United States of America, of 13500 North Central Expressway, Dallas, Texas, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to an improved seismic cable and more particularly to an acceleration-effect cancelling arrangement of pressure detectors therein.

Description of the Prior Art

Seismic cables utilized in water work are commonly referred to as streamers. In a streamer the cable and detectors are built into a single piece of equipment, sections of which are joined before they are placed in the water. The streamer is handled by a large powerful winch mounted on the stern of a survey ship. Each section includes a tube and up to 30 detectors or more. The tube, which is generally constructed of a heavy plastic, is made neutrally buoyant by being filled with a liqiud, e.g. kerosene of a plastic foam. Kerosene also provides very effective acoustic coupling from marine pressure changes to the detectors. The tension load is carried by steel wire rope strain members running the length of the streamer. Conductors are provided for feeding seismic information generated by the detectors to data recording equipment and depth information from depth transducers to a depth meter console. The signal-to-noise ratio is the ratio of the amplitude of a desired seismic signal at any time on the seismic trace to the amplitude of undesired electric disturbance (noise) signals at the same time on the trace.

The problem of enhancing the signal-to-noise ratio has long confronted the art; efforts to enhance the ratio have been made. These efforts resulted in a method of supporting the detectors within the plastic tube to make them less susceptible to random transverse accelerations and decelerations induced by towing, and to include, in detectors using piezoelectric transducers, an impedance matching step-down transformer for each detector group. This latter improvement is necessary because the output impedance of a group of such detectors is usually unacceptably high as an input to ordinary seismic amplifiers and is undesirable because of noise pickup problems.

Pressure-sensitive detectors utilize piezoelectric elements which generate an electromagnetic force (emf) when stressed by an external force applied to their surface. In the past, pressure-sensitive detectors or hydrophones employed as their piezoelectric elements anisotropic crystals such as quartz or rochelle salt. More recently, however, these anisotropic crystals have been replaced by polycrystalline and isotropic ceramic materials. An anisotropic substance exhibits different properties in different directions; while isotropic substances exhibit the same properties (e.g. electrical or optical) in all directions.

The piezoelectric elements or transducers used in hydrophones are desired to operate over a relatively large frequency range which extends up to several octaves below the device's resonant frequency. Thus they are often referred to as nonresonant transducers. The transducers comprise a ceramic dielectric having metal electrodes formed on each major surface. The electrical equivalent circuit for a nonresonant transducer can be approximated by an ideal voltage generator in series with a capacitor. The capacitor represents the electrical capacitance between the electrodes, and its value depends on the physical dimensions of the piezoelectric element and the dielectric constant of the particular type of ceramic used. The capacitance of the typical piezoelectric element used today ranges from 10 to 100 nanofarads. It is sufficient for piezoelectric elements used in hydrophones or seismic detectors to have a capacitance ranging from 9 to 11 nanofarads (nf) since using 30 such detectors in parallel results in a minus 3 dB point of approximately 6 Hz for the section. To obtain this value the thickness of the ceramic or dielectric material of the piezoelectric element must be substantially reduced. Efforts to reduce the thickness of the dielectric of prior art ceramic type piezoelectric elements of transducers which utilize as electrodes metals capable of supporting dendrite type growth such as, for example, silver failed in use because electrical short circuits developed between the electrode plates. It has been determined that these electrical shorts were the result of silver of the silver electrodes migrating through cracks in the ceramic dielectric through what is believed to be a dendrite growth type action.

Summary of the Invention

It is an object of the invention to provide an improved seismic cable or streamer.

According to the invention there is provided a seismic streamer comprising a housing, and a plurality of pressure sensitive hydrophones as herein defined mounted within said housing, at least two of said hydrophones being in a mutually spaced relationship and electrically coupled to provide a single electrical output signal and having their individual axes of sensitivity to accelaration forces selectively oriented such as to reduce in said single electrical output signal background noise owing to acceleration forces.

Each hydrophone includes a plurality of pressure sensitive detector elements connected together to produce a single electrical signal which represents pressure and which is substantially unresponsive to acceleration of the hydrophone.

The hydrophones may include piezoelectric crystals or elements having matched geometric and physical-property parameters for each pressure-sensitive detector to reduce the sensitivity of the hydrophone to acceleration and deceleration noise (hereinafter referred to as acceleration noise), by constructing a seismic cable or streamer to have its pressure-sensitive detectors connected one to the other with the polarity of one reversed as to the polarity of the other for the same acceleration noise. Thus the acceleration noise of one detector, being 180° out of phase relative to the other, subtracts from or cancels the acceleration noise of the other detector to enhance the signal-to-noise ratio of the seismic signals generated by the cable.

The seismic cable may be constructed in different ways; however, the preferred construction will be described hereinafter in conjunction with the drawings.

Brief Description of the Drawings:

FIGURE 1 is a side view of a seismic streamer being towed through water;

FIGURE 2 is a perspective view of a miniature hydrophone for use in a streamer;

FIGURE 3 is a perspective view of the miniature hydrophone subassembly.

FIGURE 4 is a sectional view of the miniature hydrophone taken along lines 4—4 of FIGURE 2;

FIGURE 5 is a schematic view of the miniature hydrophone and showing in dotted lines its response (greatly exaggerated) to pressure forces;

FIGURE 6 is a view similar to FIGURE 5 showing the miniature hydrophone's response (greatly exaggerated) to acceleration forces;

FIGURE 7 is a perspective view of the piezoelectric element;

FIGURE 8 is a diagram of the equivalent electromechanical circuit of the hydrophone of FIG. 4;

FIGURE 9 is a schematic diagram showing a pair of hydrophones of FIG. 4

arranged in a seismic streamer with the polarities as shown;

FIGURES 9A and B are waveforms of the voltage outputs of the hydrophones as arranged in FIG. 9 due to the acceleration force;

FIGURE 10 is a schematic diagram showing the same pair of hydrophones of FIG. 9 with one of the hydrophones physically oriented 180° from its position of FIG. 9;

FIGURES 10A and B are waveforms of the voltage outputs of the hydrophones as arranged in FIG. 10 due to the same acceleration force (FIG. 9); and

FIGURE 11 is a graph of the results obtained from streamers made as described herein.

Referring to the drawings, a seismic streamer 10, having a plurality of sections 12, is towed through the water at a constant depth by a ship 14. The ship 14 has a winch 16 for laying and retrieving the seismic streamer 10. The streamer 10 is made up of one or more tubular sections joined together by connectors, not shown, called integrated couplers. These couplers provide electrical continuity for all the conductor pairs from the hydrophones, hereinafter described, and the depth transducers, and water-break transducers (not a part of the present invention). In addition the couplers provide mechanical coupling for the stress members running from one end to the other of each section. Each section contains the required number of conductor pairs necessary to carry out all the hydrophone-group circuits into the instruments. Normally up to 70 pairs of conductors or more are provided, 54 of which are for seismic data, 4 are for spares, 6 are for the depth transducers and 6 are for the water-break transducers.

Each section 12 contains a plurality of hydrophones arranged in the streamer 10 in accordance with an embodiment of the invention. Referring to FIG. 2, two detector elements are arranged in a hydrophone construction which comprises a housing 20 for a hydrophone subassembly 22 (FIGS. 2 & 3). The housing 20 may be constructed of any suitable shock resistant material such as, for example, stainless steel and has its major exterior surface coated or otherwise covered with a shock absorbent and electrically resistant sleeve 21 or coating made of rubber or a suitable plastic. One end of the housing 20 supports a pair of output terminals 26 and 28 fixed thereto in insulators 29. The inner surface of the housing 20 is provided with a hydrophone subassembly mounting means 30 (FIG. 4) which may be either a groove or a series of spaced holes.

The hydrophone subassembly 22 (FIG. 3) includes a retaining means 32 (FIG. 4) adapted to mate with the hydrophone subassembly mounting means 30 to position the hydrophone subassembly within the housing 20. The retaining means 32 may be formed as an integral part of a detector element frame 34 (FIG. 4). The frame 34 has opposing ends 36 and 38 having recesses which open inwardly to receive respectively electrically conductive diaphragms 40 and 42. The frame 34 may be formed by molding any suitable plastic such as, for example, a polycarbonate plastic which after setting has the rigidity to hold the diaphragms with a reproducible compliance to pressure forces. The electrically conductive diaphragms 40 and 42 may be constructed of any suitable material such as, for example, brass, beryllium, copper, phosphor bronze or other copper alloy metal. The diaphragms are of a thickness of about 0.016 inches, the thickness criterion being that the diaphragms have sufficient strength to withstand expected hydrostatic pressures yet deform sufficiently in an acoustic pressure field to generate adequate electrical signals. The diaphragms 40 and 42 have major opposing surfaces adapted to receive respectively piezoelectric elements 44 and 46, and 48 and 50.

The piezoelectric detector elements 44—50 are identical in construction and therefore only one need be described in detail. Each piezoelectric element (FIG. 7) comprises a dielectric member 52 constructed of suitable ceramic materials such as, for example, barium titanate, lead zirconate, and lead titanate or a mixture of lead zirconate and lead titanate. Although the dielectric member 52 may be formed in any desired shape, as shown in FIG. 7 it is extruded in the form of a cylinder and then sliced into flat circular disks having a substantially uniform thickness of less than about 0.015 inches. Next, dendrite growth inhibitor metal electrodes 54 are formed on opposing sides of the ceramic disk 52. The metal must be corrosion resistant, inactive as to the constituents of the ceramic material, and insoluble or very stable as to liquids encountered by the detector element in its use environment to inhibit dendrite growth of the metal through minute cracks developing in the ceramic and subsequent short circuiting of the piezoelectric

element. A suitable metal is, for example, gold, nickel, platinum, or rhodium with gold being preferred. Gold electrodes are formed by depositing a thin layer of gold or gold frit onto the major surfaces of the ceramic disk by a thick film process to be described. A border 56 (FIG. 7) is left between the peripheries of the gold electrodes and ceramic disk to prevent short circuiting by arcing or otherwise around the edge of the ceramic disk.

The thick film process is well known to those skilled in the art; therefore, only a brief description need be given. The process consists of spreading a gold paste to a thickness of 0.0007 inches over a 200—325 mesh nylon screen and drying at room temperature for 5 to 15 minutes, and then "firing", i.e., heating to temperatures below 750°C through a conveyor type furnace with a 45 minute cycle to a peak temperature of 750°C, for 5—10 minutes to obtain good electrode adherence. Temperatures above 750°C are to be avoided to prevent damage to a lead compound ceramic disk through evaporation of the lead. A suitable gold paste is DuPont's Gold Conductor Composition 8115.

After forming the electrodes, the ceramic disk is polarized by a very powerful d.c. electric field, e.g., 40,000 to 5×10^6 V/m. A dot or other marking is used to designate the positive electrode for polarizing the ceramic disk.

Piezoelectric elements 44 and 46, and piezoelectric elements 48 and 50 are then attached by, for example, soldering with an indium alloy respectively to diaphragms 40 and 42 with the positive marked electrodes facing outwardly as indicated by the arrows in FIGS. 4, 5, and 6 to complete the hydrophone subassemblies 22.

Electrical leads 60 and 62 are then attached as shown in FIG. 5 to the electrodes that are to form the innermost plates of the hydrophone and the detector elements 58 and 58′ mounted in the recesses (FIG. 4) formed in the ends 36 and 38 of the detector element support member or frame 34 with the electrical leads 60 and 62 brought out through the detector element support member 34 (FIG. 3). Electrical leads 64 and 66 are then attached to the outermost electrodes as shown in FIG. 5 to complete the hydrophone subassembly 22.

The hydrophone subassembly 22 (FIGS. 2, 3, and 4) is then mounted in the housing 20 with the retaining means of each mating to correctly position the subassembly 22 for encapsulation with a suitable plastic such as, for example, polyurethane. After encapsulation the electrical leads 60 and 66 are attached to output terminals 26 and 28 (FIG. 2).

With the detector elements 58 and 58′ electrically connected as above described, a series-parallel relationship is established through which acceleration noise (FIG. 6) is detected and cancelled one from the other while the pressure wave (FIG. 5) is detected by both without cancellation. It will be understood that ideally the two detector elements of each hydrophone are to have the same sensitivity to acceleration so that the acceleration noise will be cancelled completely and the response of each detector element to pressure forces will be substantially equal. This desired result can be closely approximated by matching geometric and physical property parameters of the hydrophone prior to and during the construction such as, for example, by controlling the amount of encapsulating material on each side of the hydrophone. This and other parameters which can be changed are determined by equating electrical units to mechanical units in accordance with the mathematical relationship derived from an equivalent electromechanical circuit. In deriving the mathematical formula the electrical units and analogous mechanical units set forth in TABLE I are utilized.

TABLE I

Electrical Unit	Analogous Mechanical Unit
Voltage	Force
Current	Velocity
Charge	Displacement
Capacitance	Compliance
Inductance	Mass
Impedance	Mechanical Impedance

As each ceramic piezoelectric element is subjected during use to both acoustic wave (pressure) forces and acceleration noise forces the equivalent electrical circuit for these conditions is shown in FIG. 8. The pressure forces are represented in the mechanical side by F (t), and the acceleration noise forces are represented by velocity perturbations $V_o(t)$. The mass of each piezoelectric element is M, the compliance of its mounting is C_m, the electromechanical transformer has a turns ratio of N, and the capacitance C_e and output voltage E_o are shown on the electrical side. The impedance of the detector elements 58 and 58′ are represented respectively by Z_{l1} and Z_{l2}.

The equivalent circuit is divided into a mechanical side and an electrical side by the electromechanical transformers 70 and 72 for the first detector element 58 and the electromechanical transformers 74 and 76 for the second detector element 58′. The electromechanical transformers represent the electrical response to the force applied to the piezoelectric elements 44, 46, 48 and 50, respectively. The transformers 70, 72, 74 and 76 have turn ratios respectively N_1:1, N_2:1, N_3:1, and N_4:1. The mechanical side of the equivalent circuit for the first detector element 58 includes a respectively force and velocity generators 78 and 80 which are equivalent respectively to the pressure forces F(t) and the velocity disturbance perturbations $V_o(t)$. The positive terminal of these generators 78 and 80 is coupled to an inductor 82 which represents the mass (M_1) of the piezoelectric electric element 44. The inductor 82 is coupled to one end of a parallel circuit comprising a capacitor 84 which represents the compliance of the piezoelectric element 44, coupled across the primary of transformer 70. The other end of the parallel circuit is coupled through a capacitor 86 to an inductor 88 representing respectively the compliance (C_{r1}) and mass (M_{r1}) of the electrically conductive diaphragm 40. Inductor 88 is coupled to an inductor 90 which represents the mass (M_2) of piezoelectric element 46. The inductor 90 is in turn coupled to one end of a parallel circuit comprising a capacitor 92 which represents the compliance of the piezoelectric element 46 coupled across the primary winding of transformer 72. The other end of the parallel circuit is attached to the other end of the generators 78 and 80 to complete the mechanical side of the first detector element. The electrical side of the first detector element includes the following elements coupled end to end or in series: the positive terminal 26, capacitor 94 which represents the electrical capacitance (C_{e1}) of piezoelectric element 44, the secondary of electromechanical transformer 70, capacitor 96 which represents the electrical capacitance (C_{e2}) of the piezoelectric element 46, the secondary of electromechanical transformer 72, and negative terminal 28. The output of the first detector element is designated E_{o1}.

The mechanical and electrical sides of equivalent circuit of the second detector element 58′ are substantially identical to those of the first detector element 58. The principal differences are that piezoelectric elements 48 and 50 and diaphragm 42 replace the piezoelectric elements 44 and 46 and diaphragm 40. Thus the mechanical side includes a force generator 98 and velocity perturbation generator 100 which represent respectively the pressure forces F(t) and acceleration forces $V_o(t)$ exerted on the second detector element 58′. One end of the generators 98 and 100 are connected through an inductor 102 which represents the mass (M_3) of the piezoelectric element 50 to one end of a parallel circuit having a capacitor 104 which represents the compliance of piezoelectric element 50 coupled across the primary of the electromechanical transformer 74. The other end of the parallel circuit is attached to an inductor 106 which in turn is connected to a capacitor 108 which represent respectively the mass (M_{r2}) and compliance (C_{r2}) of the diaphragm 42. The capacitor 108 is coupled through an inductor 110 representing the mass (M_4) of piezoelectric element 48 to one end of a parallel circuit comprising a capacitor 112 which represents the compliance of piezoelectric element 48 coupled across the primary of electromechanical transformer 76. The other end of the parallel circuit is connected to the other end of the force and velocity generators 98 and 100 to complete the mechanical side of the second detector element. The electrical side of the second detector element comprises the following elements connected in series. From the positive terminal 26 the secondary of electromechanical transformer 76, capacitor 114 which represents the electrical capacitance (C_{e4}) of piezoelectric element 50, secondary of electromechanical transformer 74, capacitor 116 which represents the electrical capacitance (C_{e3}) of piezoelectric element 48, and negative terminal 28. The electrical output of the second detector element is designated E_{o2}.

The following mathematical formulas are derived from the equivalent circuit.

A. The voltage output owing to the same acceleration force on the first detector comprising piezoelectric elements 44 and 46 is

$$(E_{o1})_{max} = \beta(M_1 + M_2 + M_{r1})\left[\frac{A_{omax}\left(\frac{\omega}{\omega_{n1}}\right)^2}{1-\left(\frac{\omega}{\omega_{n1}}\right)^2}\right] \quad (1)$$

$$-\left[\frac{N_1 C_{m2} + N_2 C_{m1}}{C_{m1}\, C_{m2}} - \beta\left(\frac{1}{C_{m1}} + \frac{1}{C_{m2}}\right)\right]\left[\frac{A_{omax}}{\omega_{n1}^2\left[1-\left(\frac{\omega}{\omega_{n1}}\right)^2\right]}\right]$$

where

$$\beta = \frac{C_{m1}\, C_{m2}\,(C_{e1} + C_{e2}) + C_{e1}\, C_{e2}\,(N_1^2\, C_{m2} + N_2^2\, C_{m1})}{C_{e1}\, C_{e2}\,(N_1\, C_{m2} + N_2\, C_{m1})}$$

$$\omega_{n1}^2 = \frac{\frac{1}{C_{m1}} + \frac{1}{C_{m2}}}{M_1 + M_2 + M_{r1}}$$ = the square of the natural angular frequency for detector 58 mounting

B. The voltage output owing to an acceleration disturbance on the second detector comprising piezoelectric elements 48 and 50 is

$$(E_{o2})_{max} = -\Omega(M_3 + M_4 + M_{r2})\left[\frac{A_{omax}\left(\frac{\omega}{\omega_{n2}}\right)^2}{1-\left(\frac{\omega}{\omega_{n2}}\right)^2}\right] \quad (2)$$

$$-\left[\frac{N_3\, C_{m4} + N_4\, C_{m3}}{C_{m3}\, C_{m4}} - \Omega\left(\frac{1}{C_{m3}} + \frac{1}{C_{m4}}\right)\right]\left[\frac{A_{omax}}{\omega_{n2}^2\left[1-\left(\frac{\omega}{\omega_{n2}}\right)^2\right]}\right]$$

where

$$\Omega = \frac{C_{m3}\, C_{m4}\,(C_{e3} + C_{e4}) + C_{e3}\, C_{e4}\,(N_3^2\, C_{m4} + N_4^2\, C_{m3})}{C_{e3}\, C_{e4}\,(N_3\, C_{m4} + N_4\, C_{m3})}$$

$$\omega_{n2}^2 = \frac{\frac{1}{C_{m3}} + \frac{1}{C_{m4}}}{M_3 + M_4 + M_{r2}}$$ = the square of the natural angular frequency of detector 58' mounting

A_{omax} = maximum amplitude of acceleration force

C. The combined open-circuit, output of the hydrophone is given by

$$E_{oc} = \frac{Z_{12}\,E_{o1} + Z_{11}\,E_{o2}}{Z_{12} + Z_{11}}$$

where

Z_{11} and Z_{12} are respectively the electromechanical impedance of the first and second detector elements.

$$Z_{12} = \frac{C_{e4}C_{m3}C_{m4} + C_{e3}C_{m3}C_{m4} + C_{e3}C_{e4}N_3^2C_{m4} + C_{e3}C_{e4}N_4^2C_{m3}}{j\omega C_{m3}C_{m4}C_{e3}C_{e4}}$$

$$+\left(\frac{N_3\,C_{m4} + N_4\,C_{m3}}{j\omega C_{m3}\,C_{m4}}\right)\left(\frac{N_3\,C_{m4} + N_4\,C_{m3}}{\omega^2 M_{T2}\,C_{m3}\,C_{m4} - C_{m4} - C_{m3}}\right)$$

and

$$Z_{11} = \frac{C_{e2}C_{m1}C_{m2} + C_{e1}C_{m1}C_{m2} + C_{e1}C_{e2}N_1^2C_{m2} + C_{e1}C_{e2}N_2^2C_{m1}}{j\omega C_{m1}C_{m2}C_{e1}C_{e2}}$$

$$+\left(\frac{N_1\,C_{m2} + N_2\,C_{m1}}{j\omega C_{m1}\,C_{m2}}\right)\left(\frac{N_1\,C_{m2} + N_2\,C_{m1}}{\omega^2 M_{T1}\,C_{m1}\,C_{m2} - C_{m2} - C_{m1}}\right)$$

where

$$M_{T2} = M_3 + M_4 + M_{r2}$$
$$M_{T1} = M_1 + M_2 + M_{r1}$$

The parameters of a piezoelectric element or the first detector element are known or determined and fed into an automatic machine programmed to solve the mathematical formula to determine matching parameters for the remaining piezoelectric elements and the second detector element required to produce a noise cancellation hydrophone. If the corresponding parameters in the above equation are perfectly matched than the output due to acceleration is zero. These components are sorted into bins according to their voltage producing ability and selected therefrom to provide an improved noise cancellation hydrophone. This noise cancellation is referred to as first order noise cancellation.

Although hydrophones constructed to provide first order noise cancellation will under ideal conditions reduce acceleration noise output to zero, it will be apparent that in actual use it will be difficult to achieve zero noise. Thus, further acceleration noise cancellation is desirable and is provided by what is referred to as second order acceleration noise cancelling.

Second order acceleration noise cancellation is acquired by subjecting each hydrophone, prior to its incorporation into the streamer or streamer section, to a known acceleration force to determine its electrical response, i.e., its amplitude and phase response as to the acceleration force. FIG. 9 shows two hydrophones 118 and 120 coupled in parallel with their polarities such that their outputs (FIGS. 9A and B) are in phase and thus no cancellation occurs. FIG. 10 shows the same two hydrophones 118 and 120 with the polarity of response to acceleration forces of hydrophone 120 changed by turning it about in the same streamer. Although the parallel connection is the same the responses to acceleration noise as shown in FIGS. 10A and B are 180° out of phase and subtract or cancel. In this arrangement the hydrophone's response to seismic waves is not affected. The above described arrangement is only one of many that can be applied to any number of hydrophones whose acceleration noise response may vary over a range of values with improved results. Nevertheless, the ideal situation exists when the sum of the negative and positive voltage producing hydrophones approach zero and the wavelength of the acceleration noise is large compared with the length of the

section. When the noise wavelength is equal to or less than the streamer section length the spacing of the hydrophones becomes a factor in positioning the hydrophones. Further, it will be understood by those skilled in the art that the hydrophones can be rotated 90° and transverse acceleration noise cancelled in a manner similar to the cancelling of the longitudinal noise described above. Thus, various combinations of transverse and longitudinal orientations and series and parallel wiring techniques or combinations thereof can be employed, as is well known in the art, to provide any desired noise cancellation depending on knowledge of the magnitude and direction of the acceleration noise.

TABLE II lists the acceleration sensitivity measured in milliamps per gravity acceleration unit (ma/g) for 30 hydrophones. Case I represents an arrangement of the hydrophones without regard to their senses of response to acceleration or the worst case; Case II represents an arrangement of hydrophones in which their senses of response to acceleration are matched. Other methods of evaluating the hydrophones include, for example, the product of the capacitance times the acceleration sensitivity.

TABLE II.

HYDROPHONE	CASE I Acceleration Sensitivity (Unmatched)	CASE II Acceleration Sensitivity (Matched)
1	3.1	3.1
2	3.5	−3.5
3	10.5	−10.5
4	12.0	12.0
5	9.0	−9.0
6	8.5	8.5
7	8.5	8.5
8	11.0	−11.0
9	8.5	−8.5
10	12.0	12.0
11	9.0	9.0
12	9.0	−9.0
13	7.5	−7.5
14	12.5	12.5
15	10.0	10.0
16	12.5	−12.5
17	27.5	−27.5
18	30.0	30.0
19	25.0	25.0
20	20.0	−20.0
21	13.5	−13.5
22	15.5	15.5
23	21.0	21.0
24	31.0	−31.0
25	12.5	12.5
26	14.0	−14.0
27	11.0	11.0
28	12.5	−12.5
29	15.0	−15.0
30	21.0	21.0

NOTE: (−) indicates that the sense of response to acceleration is reversed.

Streamers were constructed utilizing the hydrophones of TABLE II. The first hydrophone was positioned 13.66 feet from one end coupling of the streamer, the next 14 hydrophones were equally spaced throughout the next 54.67 feet of the streamer, the 16th hydrophone was positioned 27.33 feet further along the streamer, there being no hydrophones positioned within the center 27.33 feet of the streamer, the remaining 14 hydrophones were equally spaced within the next 54.67 feet of the streamer; and the other end coupling was spaced 13.66 feet from

the last hydrophone. With streamers so constructed trial runs were made with the results shown in FIGURE 11 in which the relative response of the streamers to acceleration forces are plotted on the ordinate axis against the wave number K in cycles per foot and the corresponding wavelength λ in feet per cycle. The chart clearly shows the improved performance where the wavelength of the acceleration noise is large as compared to the length of the section. Nevertheless, by arranging the acceleration polarities of the hydrophones to accord with desired acceleration force noise wavelengths improved performance is obtained.

It will be understood that others skilled in the art can make other changes in the construction of the embodiments of this invention without departing from its scope.

WHAT WE CLAIM IS:—

1. A seismic streamer comprising a housing, and a plurality of pressure sensitive hydrophones as herein defined mounted within said housing, at least two of said hydrophones being in a mutually spaced relationship and electrically coupled to provide a single electrical output signal and having their individual axes of sensitivity to acceleration forces selectively oriented such as to reduce in said single electrical output signal background noise.

2. A seismic streamer according to claim 1 wherein said at least two hydrophones are spaced along the streamer and oriented such as to reduce the noise owing to acceleration forces of a given wavelength and propagating in a given direction with respect to said streamer.

3. A seismic streamer according to either of claims 1 and 2 wherein, for a given acceleration of said streamer, the voltage induced in at least one hydrophone of said at least two hydrophones is of a polarity opposite to that of another hydrophone.

4. A seismic streamer according to any preceding claim wherein the axes of sensitivity to acceleration of the hydrophones are positioned transverse to the longitudinal axis of the streamer.

5. A seismic streamer according to any preceding claim wherein each of said pressure sensitive hydrophones includes a plurality of pressure sensitive detector elements having matched geometric and physical property parameters, and electrical conductors leading from the elements, said elements being mounted in said housing and the electrical conductors coupled so that the outputs of the elements owing to acceleration forces substantially cancel.

6. A seismic streamer according to claim 5 wherein each of said hydrophones includes an electrically conductive diaphragm, a pair of piezoelectric elements each mounted on a major surface of the diaphragm and electrical conductors attached to the piezoelectric elements, said piezoelectric elements and diaphragm of one hydrophone having geometric and physical property parameters matching those of another hydrophone.

7. A seismic streamer according to either of claims 5 and 6 wherein the electrically coupled pressure sensitive hydrophones mounted in the housing are encapsulated.

8. A seismic streamer according to any of claims 1 to 5 wherein each of said plurality of pressure sensitive hydrophones includes a plurality of pressure sensitive hydrophone subassemblies with each subassembly having a plurality of piezoelectric transducer elements operatively mounted in said subassembly for seismic wave detection, each piezoelectric transducer element having a dielectric and metal electrodes stable in aqueous solutions to inhibit dendrite growth.

9. A seismic streamer according to claim 8 wherein said metal electrodes are comprised of gold.

10. A seismic streamer according to either of claims 8 and 9 wherein each of said piezoelectric transducer elements includes a ceramic dielectric.

11. A seismic streamer according to claim 10 wherein said ceramic dielectric comprises a mixture of lead zirconate and lead titanate.

12. A seismic streamer according to claim 5 wherein the geometric and physical property and electrical parameters which are matched are, for the electrical side, voltage output (E_o) of each piezoelectric element, the capacitance (C_{ex}) of each piezoelectric element; and for the mechanical side: pressure force (F) acting on each detector element owing to acoustic forces and a velocity perturbation force (V) owing to acceleration and deceleration forces, compliance (C_{mx}) of each element mounting, mass (M_x) of each piezoelectric element and diaphragm (M_{rp}), turns ratio (N_x) representing electromechanical transformer action of each piezoelectric element and the mechanical impedance (Z) of each

detector element, where x equals 1, 2, 3, or 4 indicating the particular piezoelectric elements and p equals 1 or 2 indicating the particular diaphragm.

13. A seismic streamer substantially as herein described and as illustrated by the accompanying drawings.

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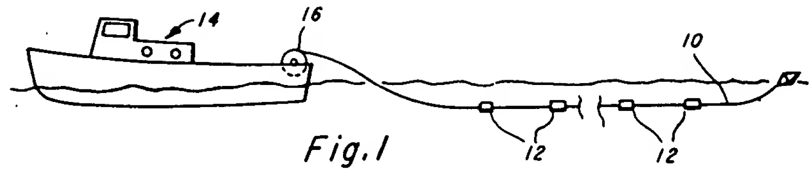

Fig. 1

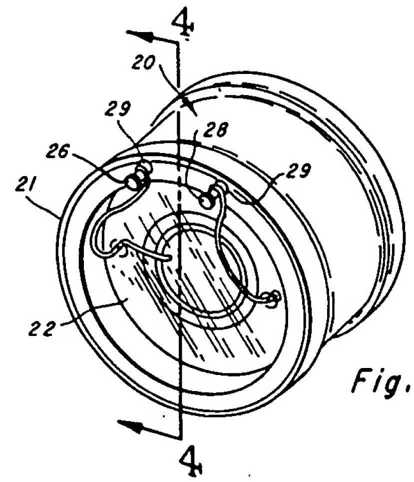

Fig. 2

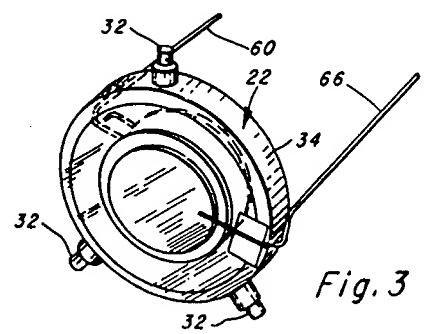

Fig. 3

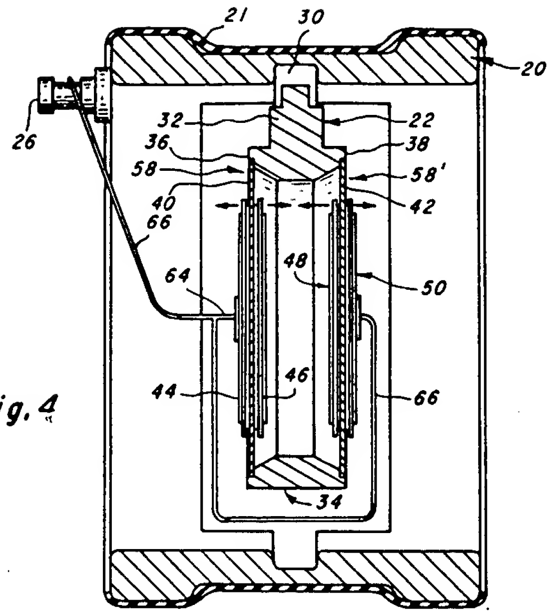

Fig. 4

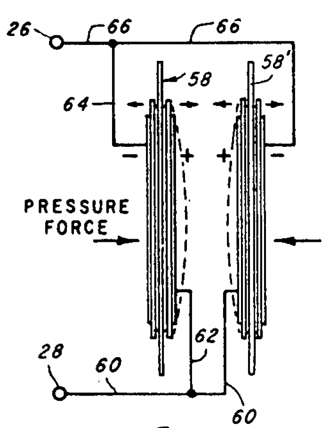

Fig. 5

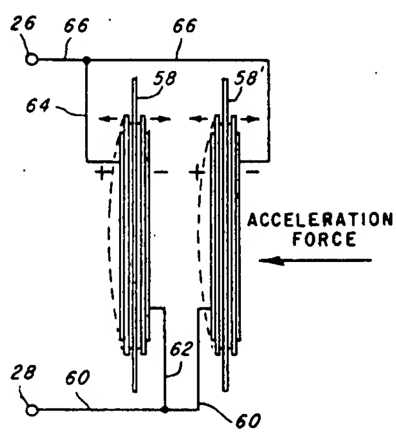

Fig. 6

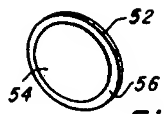
52
54
56

Fig. 7

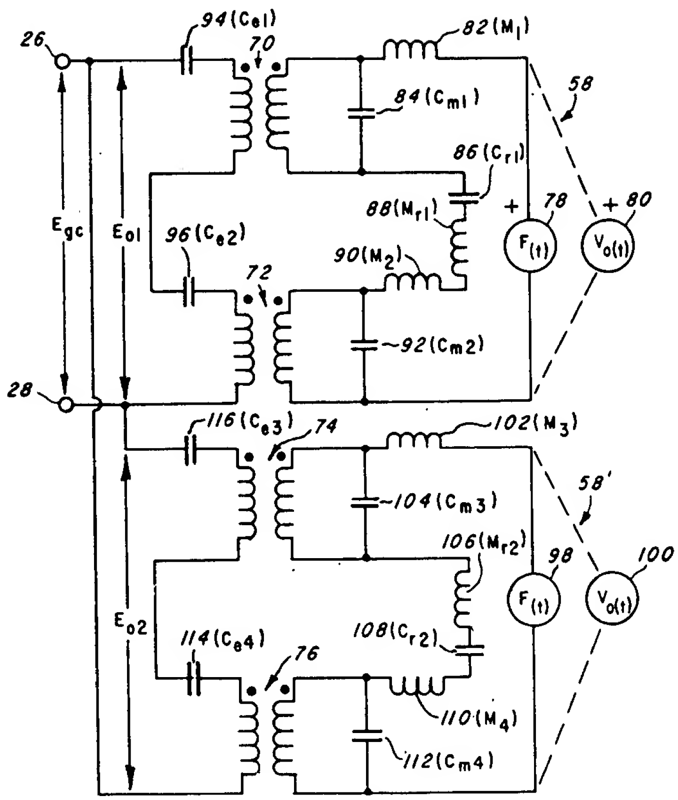
26
28
94 (Ce1)
70
82 (M1)
84 (Cm1)
86 (Cr1)
88 (Mr1)
58
78
80
F(t)
V0(t)
Egc
E01
96 (Ce2)
72
90 (M2)
92 (Cm2)
116 (Ce3)
74
102 (M3)
104 (Cm3)
58'
106 (Mr2)
98
100
E02
114 (Ce4)
76
108 (Cr2)
110 (M4)
112 (Cm4)

Fig. 8

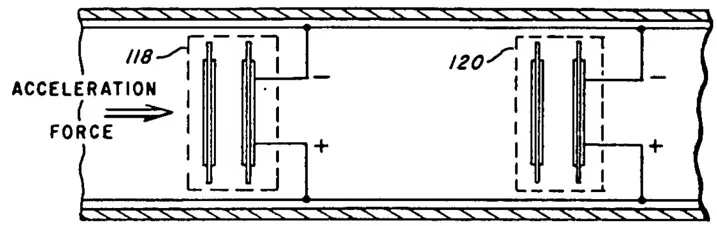

Fig. 9

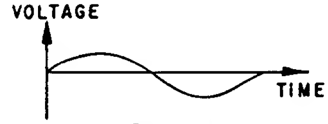

Fig. 9A

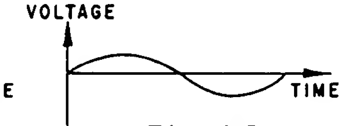

Fig. 9B

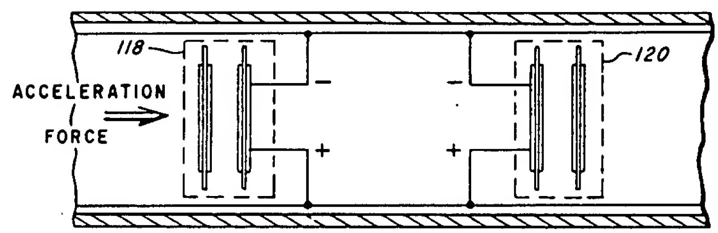

Fig. 10

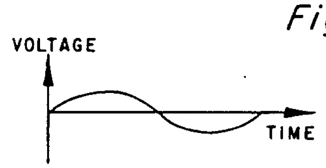

Fig. 10A

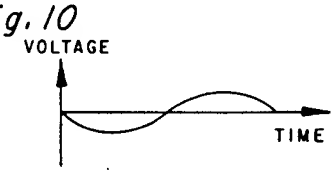

Fig. 10B

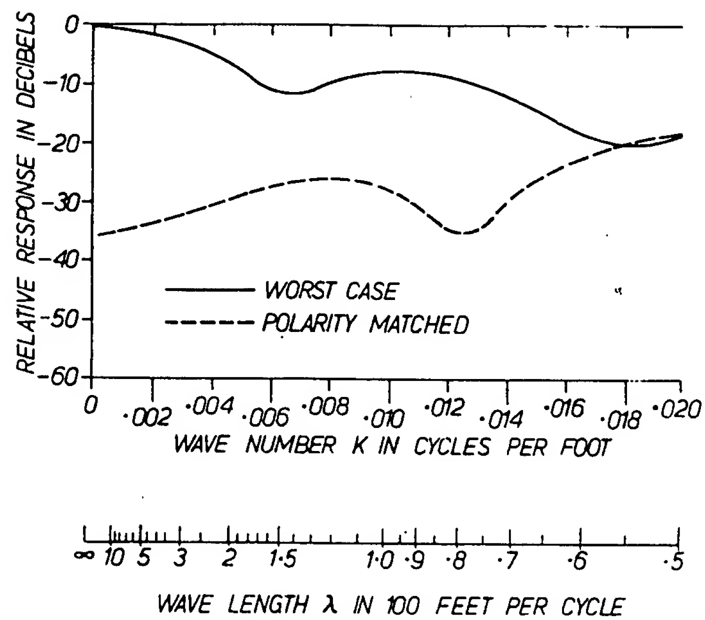
RELATIVE RESPONSE IN DECIBELS
0
-10
-20
-30
-40
-50
-60
WORST CASE
POLARITY MATCHED
0
·002
·004
·006
·008
·010
·012
·014
·016
·018
·020
WAVE NUMBER K IN CYCLES PER FOOT
∞ 10 5 3 2 1·5 1·0 ·9 ·8 ·7 ·6 ·5
WAVE LENGTH λ IN 100 FEET PER CYCLE

FIG. 11.